

Mock Data Challenge Generation Package

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T. Regimbau and D. Meacher

with contribution from

J. Clark, M. Coughlin, J. Gair, I. Kowalska, I. Mandel, C. Rodriguez*

*Electronic address: regimbau@lapp.in2p3.fr

I. OBJECTIVE

The purpose of the MDC Generation Package is to produce simulated data to prepare the data analysis and science with the future generations of gravitational-wave experiments, such as Advanced LIGO-Virgo or Einstein Telescope. The end product are the time series of the detector outputs, arising both from the instrumental noise and from the GW signal. It follows the procedure developed for the Einstein Telescope mock data challenge (ET-MDC) for binary neutron stars [1, 2], extended to all type of binaries [2–4] and then to a larger variety of sources (supernovae, stochastic backgrounds). In this document, we describe the structure of the MDC Generation Package, and explain how to produce simulated data samples. The package is available on demand

II. MDC CODE STRUCTURE

The schematic structure of the MDC Generation Package is presented in Fig. 1. It contains different modules which are shortly described below. Each module can be developed independently in order to make the package more flexible. The package uses the LIGO Algorithm Library (LAL) and GSL. Some extra codes are written in Matlab or Mathematica.

1. **Monte-Carlo Simulations** : The core of the program, which simulates the time series, is shown inside the central red box. This module has been implemented for the first ET-MDC and has not changed significantly. As described in [1], the sources are realistically distributed in the parameter space (e.g mass, spin, inclination, polarization, phase), but also in time, assuming a Poisson distribution of the arrival times, redshift, accounting for the star formation history of the Universe (see module "Universe") and location in the sky. The noise is generated from the PSD of the detector (see module "Detector") and tapered to avoid discontinuities at boundaries between data segments.
2. **Universe** : This module contains information on the Universe, locally or at cosmological distances : cosmological parameters, star formation history, initial mass function, metallicity, catalog of galaxies. All these informations are needed to calculate the source rates, the distribution in redshift as well as the luminosity distances. Galaxy catalogs are not yet included but their implementation is an ongoing project.

3. **Sources** : This module is constantly evolving. It contains the probability distributions of the source parameters (masses, spins etc...) that are needed to simulate realistic populations of sources. The package uses analytical models or results of the star evolution codes StarTrack for stellar compact binary systems [5]. It also contains a bank of burst waveforms, and a catalog of spectra for GW stochastic backgrounds ¹ used to generate the GW signal in the frequency domain before being Fourier transformed into the time domain.
4. **Detectors** : This module contains all the informations related to the detectors : geometry, location, response tensors (needed to calculate the beaming factors) and various models for the sensitivity. By default, we generate Gaussian colored noise but non Gaussian noise containing glitches can also be produced.

III. NOISE

The noise generation routine was provided by Carl Rodriguez for the first ET MDC [1]. The noise is simulated by generating a Gaussian time series with a mean of zero and unit variance. This time series are then taken into the frequency domain, colored with the noise PSD, and then inverse Fourier transformed. Because of the Fourier transform, the duration of noise segments has to be a power of 2, for example, 64s, 128s, 512s, 1024s, 2048s etc... To alleviate the effects of any potential discontinuities across frame files, the noise curve is gradually tapered away to zero below f_{Min} , and above $f_{Nyquist}/2$.

At the moment the code generates data for a network of 2G detectors composed by the 2 LIGO and Virgo or the 3G detector Einstein Telescope (ET). It may be extended in the future to include KAGRA and LIGO India for the 2G network and Cosmic Explorer in the US for 3G. The design noise curves for aLIGO, AdVirgo, and KAGRA, and for the proposed 3G detectors Einstein Telescope and Cosmic Explorer (CE) are in the directory **Input** (see Fig. 2). If you want to use other PSDs, you can just replace these files by your favorite ones or choose one of the noise models that can be found in the directory **Detector**. For exemple, you can produce 3G data for the LIGO-Virgo network using the sensitivity of Cosmic Explorer (CE.txt).

¹ <http://homepages.spa.umn.edu/cwu>

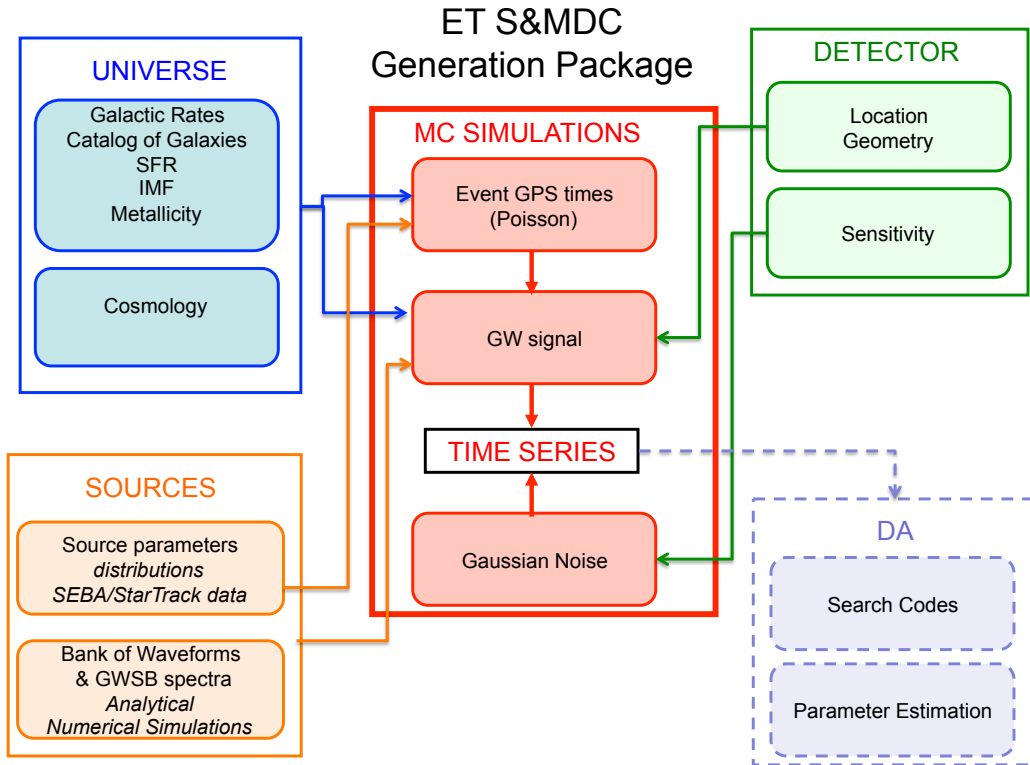


FIG. 1: Structure of the ET Generation package. The different modules are independent and can be developed separately. The module Data Analysis, which is not part of the generation package but uses the simulated time series.

We noticed strange behavior at frames boundaries when using sensitivity curves with narrow peaks. To avoid this problem we strongly recommend using smooth versions of the noise curves.

IV. THE MODEL OF UNIVERSE AND THE COSMIC RATE

By default, we assume a Λ CDM cosmology and regularly update the cosmological parameters. We are currently using the 2018 combined results for Planck+BAO ² that gives $H_0 = 67.9$ km/s/Mpc, density of matter $\Omega_m = 0.3065$, density of dark energy $\Omega_\Lambda = 1 - \Omega_m$. The file *dL.txt* in the directory **input**, contains the luminosity distance as a function of the

² i.e. the last column of Table II of <https://arxiv.org/pdf/1807.06209.pdf>

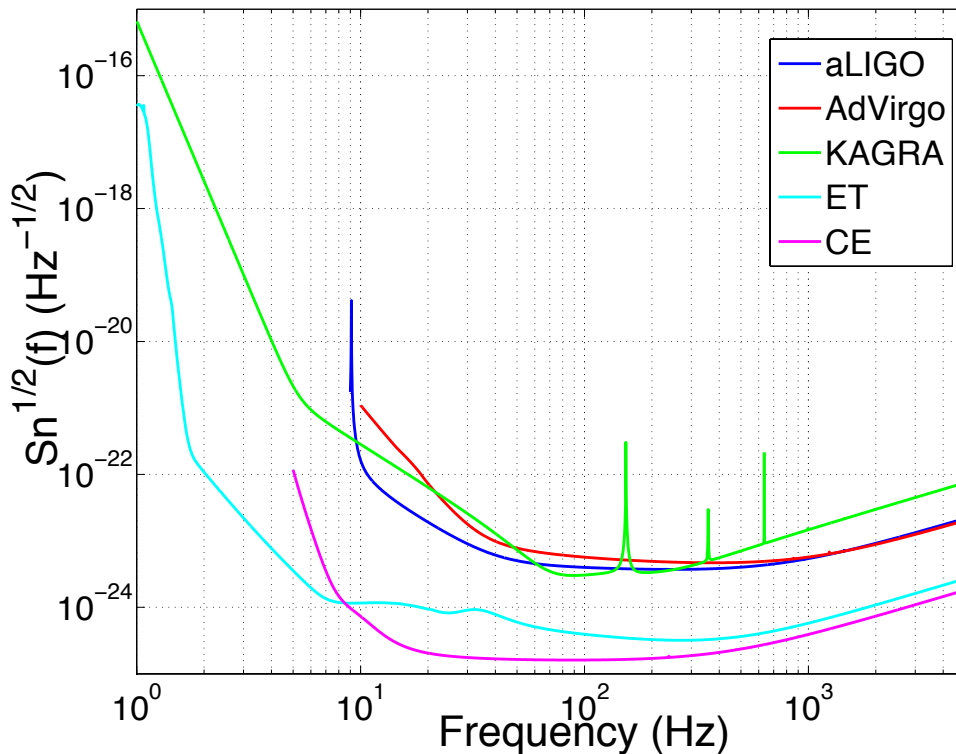


FIG. 2: Sensitivity curves for Advanced LIGO, Advanced Virgo, KAGRA, Einstein Telescope (ET-D) and Cosmic Explorer.

redshift up to $z = 10$ (see Fig. 3). For other cosmologies, the package provides a Mathematica code `cosmo_functions.nb` and a Matlab code and `cosmo_functions.m` in the directory **Cosmology** where the user can change the cosmological parameters and generate a new file `dL.txt`. The package contains a few models of star formation rates in the Matlab code `cosmic_rates.m`: old ones (see Fig 4) [6] for details and references) and the most recent ones used by the LIGO/Virgo stochastic group [7, 8]. They are needed to derive realistic probability distributions of the redshift, as we will see in the next section.

V. THE POPULATION OF COMPACT BINARIES

Compact binaries coalescences (CBC) have started to be detected by Advanced LIGO/Virgo and will be seen by Einstein Telescope and Cosmic Explorer at very large distances. On the other hand, the background created by the superposition of all the individual sources

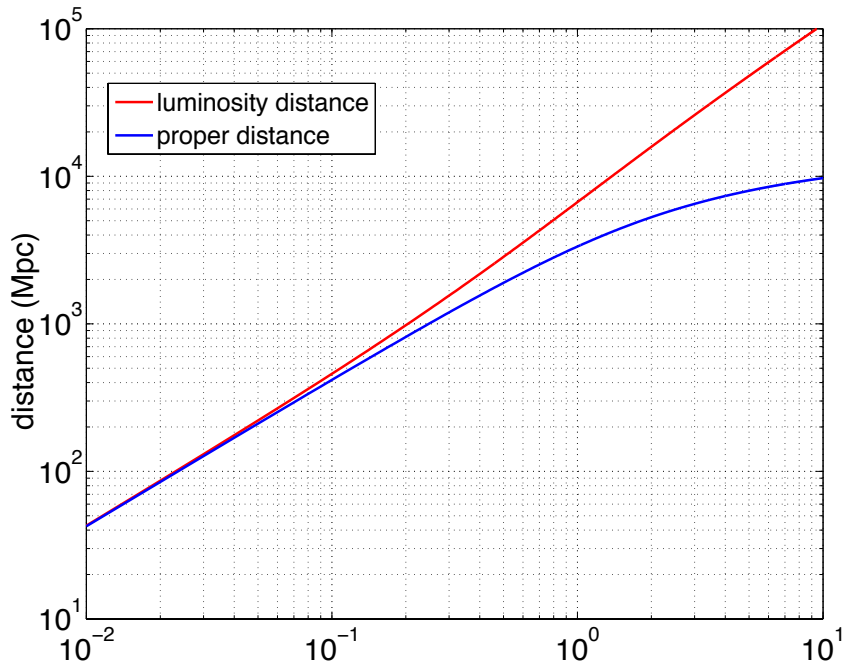


FIG. 3: Proper distance and luminosity distance for a flat Universe with $H_0 = 70.$ km/s/Mpc, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

up to a redshift of $z \sim (5 - 10)$ has a realistic chance to be detected by advanced detectors [9, 10].

The generation code *simul.c* simulates the GW signal from the entire population taking the source parameters from ascii files *cbc_0.dat*, *cbc_1.dat* etc... stored in the directory **lists** (one file for each data segment). The package provides the code *list_cbc.c* to generate lists of parameters for realistic simulated populations.

A. Simple Model

The simple model has been used to generate the extra-galactic populations of double neutron stars (BNS) for the first ET-MDC (see[1] for details). It has been extended to include populations of two black holes (BBH) or a black hole and a neutron star (BH-NS).

- the time intervals between successive events is drawn from an exponential distribution $P(\tau) = \exp(-\tau/\lambda)$, assuming Poisson process. The average waiting time λ can be

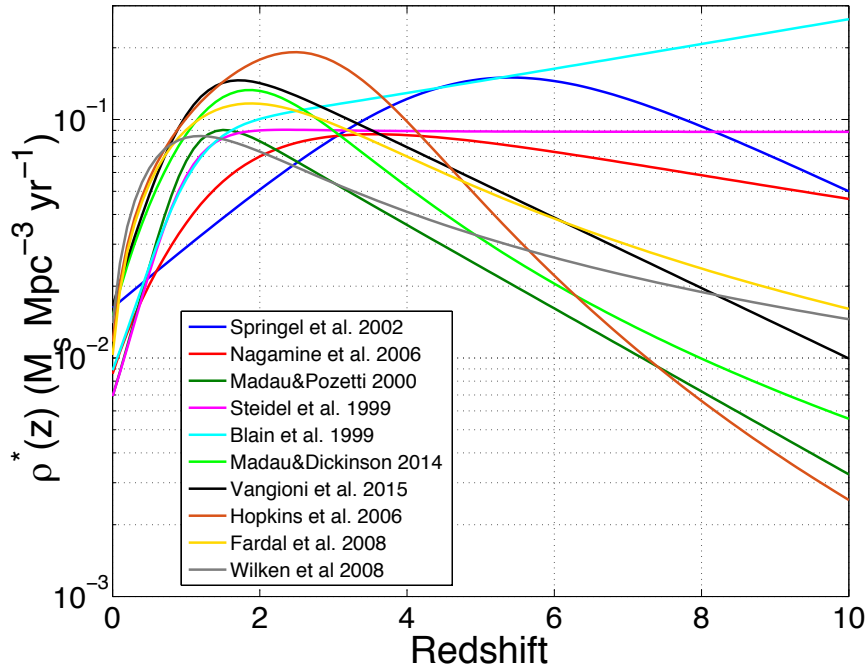


FIG. 4: Different models of the star formation rates. See see [7, 8, 8] for references and details.

calculated by taking the inverse of the merging rate integrated over all redshifts. Fig. 5 shows λ as a function of the maximal redshift z_{\max} for a population of BNS, assuming a local rate of $\rho_0 = 1 \text{ Myr}^{-1} \text{ Mpc}^{-3}$ and the SFR of [11] as assumed in [1]. For the most recent model and local rates derived from the first LIGO/Virgo observations see [10].

- the user specifies in the command line the fraction of BNS, BBH and BH-NS. The type of the sources is randomly selected accordingly.
- the redshifts are drawn from a probability distribution $p(z)$ provided in ascii files *Pz_BNS.txt* for BNS and *Pz_BBHa.txt* or *Pz_BBHb.txt* for BH-NS and BBH³, in the directory **input**, in which the code interpolates. This probability is obtained by normalizing (in the interval 0 – 10) the coalescence rate $dR_c^o/dz(z)$, which is obtained by

³ The probability *Pz_BBHb.txt* is used when one of the component is larger than $30 M_{\odot}$. It accounts for the fact that BHs with such a large mass can form only in a low metallicity environment ($Z < Z_{\odot}/2$)[9]

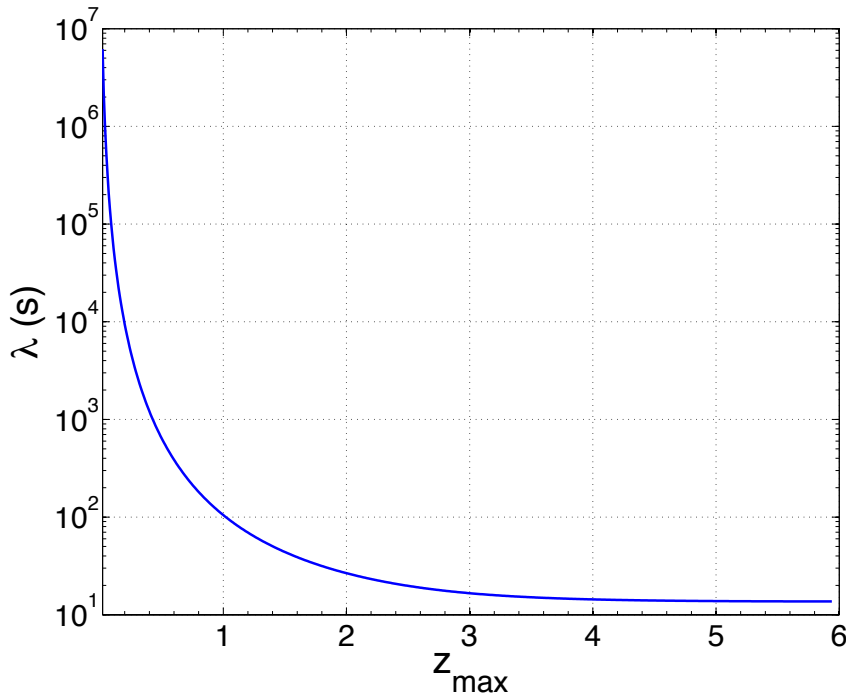


FIG. 5: average waiting time between successive BNS coalescences as a function of the maximal redshift, assuming the SFR of [11] and a local rate of $\rho_0 = 1 \text{ Myr}^{-1} \text{ Mpc}^{-3}$.

multiplying the element of comoving volume $\frac{dV}{dz}$ by the cosmic coalescence rate:

$$\dot{\rho}_c^o(z) \propto \frac{\int \dot{\rho}_*(z_f) P(t_d) dt_d}{1+z} \quad \text{with } \dot{\rho}_c^o(0) = \dot{\rho}_0 \quad (1)$$

In this equation, $\dot{\rho}_c$ is the star formation rate, z_f the redshift at the time of formation of the massive binary system and $P(t_d)$ the probability distribution of the delay between the formation and the coalescence. We assume a distribution of the form $P(t_d) \propto 1/t_d$ with a minimal delay of 20 Myr as representative of the population of BNS, and with minimal delay of 50 Myr as representative of the populations of BH-NS and BBH [10]. The codes *cosmic_rates.m* and *cosmic_rates.nb* can be used to produce new files for other SFR and probability distribution of the delay.

- we provide different distributions from which the masses of the two components m_1 and m_2 can be drawn. For neutron stars the user can specify a fixed mass or choose a uniform or a Gaussian distribution (in these cases the user specifies the mean, the variance, the minimal and the maximal masses from the command line). For black

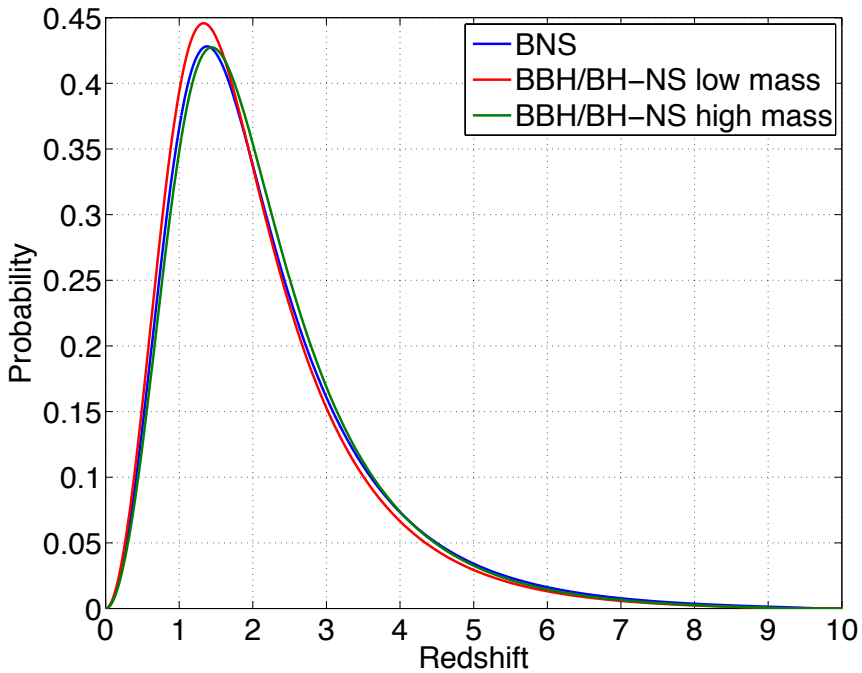


FIG. 6: probability distribution of the redshift for the population of BNS (blue) and NS-BH or BBH (red), assuming the SFR of [7] and a probability distribution of the delay of the form $P(t_d) \propto 1/t_d$ with a minimal delay of 20 Myr (BNS) and 50 Myr (BH-NS or BBH).

holes there is also the possibility to choose one of the two astrophysical distributions used by the LIGO/Virgo collaboration for O2 and considered in [10]: 1) a power-law distribution of the primary (i.e., larger mass) companion $p(m) \propto m^{2.35}$, and uniform distribution of the secondary 2) a uniform distribution in the logarithm of the component masses $p(m) \propto m^{-1}$.

- the spin parameters χ_1 and χ_2 of the two components are drawn from a uniform distribution in the range $[-1 - 1]$.
- the location in the sky, the orientation, the polarization and the phase at the coalescence are drawn from uniform distributions

B. Population Synthesis Model

The second model takes as input lists of parameters (the mass of the two components and the redshift), provided by I. Kowalska and derived from the binary evolution code StarTrack [12], assuming the SFR of [11]. Note that only the standard model is provided with the package and it is outdated. For more rrecent models one can visit the website syntheticuniverse.org. In addition, lists of parameters for IMBH or IMRI up to a redshift of $z \sim 3$ have been provided by J. Glair and I. Mandel [13, 14]. All these files, *list_BNS.txt*, *list_BBH.txt* etc... are stored in the directory **Input**. The type, the location in the sky, the orientation, the polarization and the phase at the coalescence are drawn from uniform distributions as for the simple model.

VI. BURSTS

The directory **Input** contains a few ascii files with burst waveforms (2 supernovas and 6 f-modes, provided by J. Clark), that can be rescaled and injected in the data. All the files contains 3 columns: time, h_+ , h_\times . The first supernova waveform (*bWform_10.txt*) is a model of Dimmelmeier, the second a model of long bar (*bWform_11.txt*). Both have optimal orientation (the inclination angle is taken into account later in the generation code). There are 6 signals for f modes, 3 for $l = 2, m = 0$ (*bWform_200.txt*, *bWform_201.txt* and *bWform_202.txt*) and 3 for $l=m=2$ (*bWform_200.txt*, *bWform_201.txt* and *bWform_202.txt*). Those have random inclinations and phases.

VII. HOW TO RUN THE CODE TO PRODUCE SIMULATED DATA

In this section we provide instructions to start quickly with the generation code. Please do not hesitate to contact us for further explanations (tania.regimbau@lapp.in2p3.fr).

A. Installation

First, you have to install and compile the LAL library. Instructions are given here: <https://www.lsc-group.phys.uwm.edu/daswg/projects/lalsuite.html>.

Next, request the package by sending an email to tania.regimbau@lapp.in2p3.fr, or if you

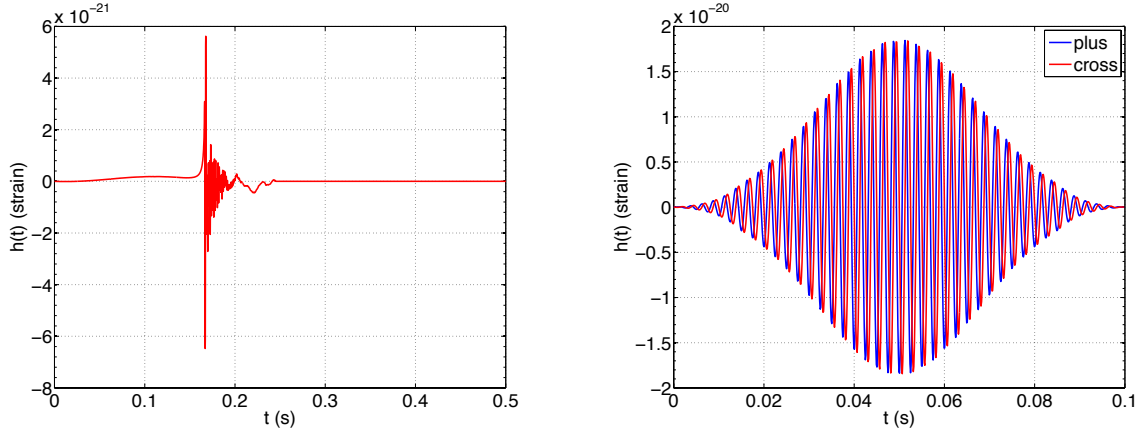


FIG. 7: supernova waveforms included in the package, a model of Dimmelmeier (left) and a long bar (right), both at 10 kpc. For the model of Dimmelmeier we only show the polarization h_+ , the h_\times polarization being 0.

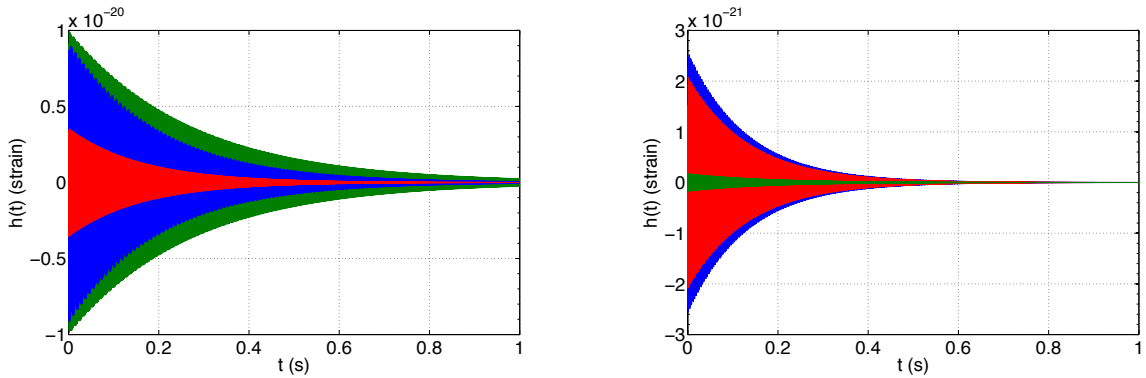


FIG. 8: f-modes waveforms included in the package, 3 models with $m = 2$ and $l = 0$ (left), and 3 models with $m = 2$ and $l = 2$ (right), both at 1 kpc. We show only the polarization h_+ , the h_\times polarization being 0 for $l = 0$ and comparable to the h_+ polarization for $l = 2$.

are in the LIGO/Virgo collaboration you can get the package from the git repository (see https://git.ligo.org/stochastic/MDC_Generation)⁴.

The codes can be compiled by running the command *make*. It produces four main executables

⁴ in this case I would ask you not to push any change. If you notice something that you feel should be modified please send us an email first

bles : *list_cbc*, *simul*, *snr*, *back*. Edit the file *Makefile*, and choose between "for use on local machines" or "for use on clusters". By default the last one is commented.

B. Produce parameter lists

For each data segment, you need to provide files with the parameters of the sources you want to inject (*cbc_j.dat* for CBCs and for bursts *burst_j.dat* for bursts, *j* being the segment number).

For CBCs, the parameters are : source number, starting time (GPS), masses of the two components (in M_{\odot}), the spin parameters of the two components, luminosity distance (Mpc), right ascension, decl, polarization, inclination and initial phase (in rad), type (1 for BNS, 2 for BH-NS, 3 for BBH, 4 for IMRI, 5 for IMBHB in GC, and 6 for IMBHB seed). In addition a file containing the sources for all the segments *list_cbc.txt*, is created with additional information: GRB detection (0=no, 1=yes), signal to noise ratio (if requested). You can provide your own lists of parameters or use the code *list_cbc.c* described in the previous section. You can also use this code as a template for your own models.

For the bursts, the parameters are: source number, starting time (GPS), distance (kpc), right ascension, declination, polarization and inclination (in rad), model. Note that for the supernova waveforms, the polarization and the inclination will not be used as they are already taken into account in the waveform file. These waveforms in the files are sampled at 8192 Hz but are resampled in the case another sampling rate is used to generate the data. The model codes are : Dimmelmeier waveform (code 10), long Bar model (code 11), f modes $m = 2$ and $l = 0$ (code 200, code 201, code 202), f modes $m = 2$ and $l = 2$ (code 220, code 221, code 222).

The command menu can be output with the option -h:

```
./list_cbc -h
```

```
Usage: pipeline [options]
```

```
Options:
```

```
-h                print this message
-s                seed for random generation
-t                starting GPS time
```

-d average time interval between events
 -r sampling rate
 -f minimal frequency
 -l segment duration
 -S number of data segments
 -p fraction of BNS
 -P fraction of BHNS
 -q fraction of BBH
 -Q fraction of IMRI
 -j fraction of IMBHB_GC
 -J fraction of IMBHB_seed
 --nocbc remove BBH, BHNS and BNS
 --noimbh remove IMBHB
 --no-detect remove sources above threshold
 -z minimal redshift
 -Z maximal redshift
 --proba randomly select z, m1, m2 from distributions for BBH, BHNS and
 -X spin distribution: 0 spin, 1 uniform
 -k mass distribution of NSs: 0 fixed value, 1 uniform, 2 Gaussian
 -K mass distribution of BHs: 0 fixed value, 1 uniform, 2 Gaussian
 -m minimal mass of NSs
 -M maximal mass of NSs
 -a mean of the mass distribution of NSs
 -b standard deviation of the mass distribution of NSs
 -n minimal mass of BHs
 -N maximal mass of BHs
 -u mean of the mass distribution of BHs
 -v standard deviation of the mass distribution of BHs
 -G beaming angle in degrees for GRB (BNS and BHNS)

 --ALV calculation of the SNR for ALV
 -R set SNR threshold to remove detectable events (Default (-1) =)

-w max redshift to calculate SNR for BNSs
 -x max redshift to calculate SNR for NSBHs
 -y max redshift to calculate SNR for BBHs

for Condor use only, split the data into intervals, each containing -S \$value data se

-I number of intervals (by default 1)
 -i # of the interval (by default 0)
 --simul write observed parameters in extra files for simulations

Typical commands look like:

1. `./list_cbc -S 1000 -l 2048 -r 8192 -f 10 -t 800000000 -d 20 -p 0.85 -P 0.02 -q 0.13 -Q 0 -j 0 -J 0 -z 0 -Z 10 --proba -m 1 -M 3 -a 1.4 -b 0.1 -n 5 -N 13 -u 15 -v 3 -G 20 --simul`

This generates lists for 1000 segments of duration 2048 s, sampled at 8192 Hz, with minimal frequency 10 Hz, the first segment starting at GPS 800000000. The average waiting time between coalescences is 20 s. The population contains 85% of BNS, 2% of NH-NS and 13% of BBH, with redshift between 0 – 10. The masses (in unit of solar mass) of NS and BH are randomly selected from Gaussian probability distributions of mean 1.4 for NS (15 for BH) and standard deviation 0.1 for NS (3 for BH). The NS masses are selected between 1 – 4 and the BH masses between 5 – 9. The half beaming angle of GRB is assumed to be 20 degrees.

2. `./list_cbc -S 1000 -l 2048 -r 8192 -f 10 -t 800000000 -d 200 -p 0.8 -P 0.02 -q 0.12 -Q 0.03 -j 0.02 -J 0.05 --simul`

This generates lists for 1000 segments of duration 2048 s, sampled at 8192 Hz, with minimal frequency 10 Hz, the first segment starting at GPS 800000000. The average waiting time between coalescences is 200 s. The population contains 85% of BH-NS, 2% of BH-NS, 13% of BBH, 3% of IMRI, 2% of seed IMBHB and 5% of IMBHB is globular cluster. The range of redshift is 0 – 10 (by default) for stellar CBC and up to 4 for IMBH populations. The masses of the two components and the redshift are read from ascii files.

3. `./list_cbc -S 154 -l 20480 -r 4096 -f 10 -t 800000000 -d 13 -p 0.95 -P 0 -q 0.05 -Q 0 -j 0 -J 0 -z 0 -Z 10 --proba -k 1 -K 3 -m 1 -M 2 --simul`

This command generates lists for about a year of data for a model corresponding to the rates and the mass distributions deduced from the first observations run O1 and O2 and used in [10]. We assume a flat mass distribution for BNS in the range $1 - 2 M_{\odot}$ and an exponential distribution for the BH masses.

4. One can use condor to produce lists for a long observation time. In this case the data will be split into intervals, each interval being run on a different node. In order to produce 10×1000 segments using 10 nodes, one would do (`$job = 0,1...9`):

`./list_cbc -i $job -I 10 -S 1000 -l 2048 -r 8192 -f 10 -t 800000000 -d 200 -p 0.8 -P 0.02 -q 0.12 -Q 0.03 -j 0.02 -J 0.05 --simul`

There are also a few extra commands that can be useful for specific projects :

- The flag `-ALV` can be used for stochastic MDC, to remove from the lists all the sources detected by the network Advanced LIGO/Virgo with a signal-to-noise ratio larger than the value set by the command `-R`. We recommend to specify a range of redshift where the sources can be detectable in order to avoid losing time calculating the signal-to-noise ratio for all the sources at high redshift.
- The flags `-no-scbc` and `-no-imbh` can be used to isolate stellar CBC or IMBHB/IMRI populations, by removing either the stellar CBCs or IMBHBs/IMRIs, but keeping exactly the same parameters for the remaining sources.

The package provide also an extra code to calculate quickly the signal-to-noise ratio from a list produced by the code `list_cbc.c`, for networks of 2G detectors (LIGO+Virgo and LIGO+Virgo+LIGO India+KAGRA) and 3G detectors (ET, LIGO+LIGO India+KAGRA with the sensitivity of CE and ET + LIGO+LIGO India+KAGRA with the sensitivity of CE). All these SNR are added as 5 new columns in the file `list_cbc_snr.c`. The code can be run with the command `./snr`.

C. Generate data

The user can specify whether noise should be added to the data (option *-noise*), and what gravitational signal should be included (options *-scbc* for the population of stellar compact binaries, *-imbh* for IMBHB and IMRI, *-burst* for occasional supernovas and f modes, *-sgwb* for a gaussian stochastic background or *-agwb* for a population of sine-gaussian or ring down signals mimicking a (non Gaussian) background of identical sources (type *-h* for help).

For now, we use TaylorT4 waveforms for BNS and BH-NS (soon with tidal corrections), and EOBNv2 waveforms for BBH, IMBHB and IMRI, but it is possible to edit the codes and choose any of the templates included in the LAL library.

The generation code menu can be output with the option *-h* :

Usage: pipeline [options]

Options:

- h print this message
- verbose verbose mode
- ascii write to ascii files
- params write source parameters to file
- ET select ET detectors (cannot select both ET and ALV)
- ALV select ALV detectors
- virgo include Virgo in ALV
- nul 1 produce null stream for ET (with --ET flag)
- single use simple precision
- noise generate noise
- sgwb simulate sgwb
- scbc simulate stellar cbc
- imbh simulate IMBBHs and IMRIs
- burst simulate burst
- agwb simulate background of sine-gaussians or ringdown
- s seed for noise generation
- j job number
- J start job number
- t start time of the serie

-l segment duration
 -L segment duration for noise generation
 -r sampling rate of the time serie
 -f minimal frequency
 -F reference frequency for sgwb
 -o reference omega for sgwb
 -I power index sgwb
 -H Hubble parameter
 -a amplitude factor for CBC
 -b sine-gaussian or ringdown frequency for agwb. Set to 0 for uniform between 10-500
 -B sine-gaussian or ringdown decay time for agwb
 -m duty cycle for agwb
 -w waveform for agwb : (0: sine-Gaussian(default) 1: ringdown)
 -R working directory

Typical commands are :

1. `./simul -t 800000000 -j 0 -l 2048 -r 8192 -f 5 --ET --noise --scbc --!imbh --burst`

This generates 3 frames in the directory **output** (E1-E1:STRAIN-800000000-2048.gwf, E2-E2:STRAIN-800000000-2048.gwf and E3-E3:STRAIN-800000000-2048.gwf,) starting at GPS time 800000000, of length 2048 s, sampling rate 8192 Hz, with minimal frequency 5 Hz, containing ET noise, the CBC population (stellar CBCs, IMBHBs and IMRIs) and a burst.

If you want to output the time series as ASCII files rather than frames, add the option “--ascii”. It will produce a single file *serie_0.dat* in textbfoutput, the first column being the GPS time and the next three columns $h(t)$ for the three ET detectors.

2. `./simul -t 800000000 -j 2 -l 20480 -L 2048 -r 4096 -f 10 --noise --scbc -a 3`

This will generate 2 frames in the directory **output** (H1-H1:STRAIN-800004096-2048.gwf and L1-L1:STRAIN-800004096-2048.gwf,) starting at GPS time 800004096, of length 20480 s, sampling rate 4096 Hz, with minimal frequency 10 Hz, containing aLIGO noise and the stellar CBC population. The option ‘-a 3’ tells the code to

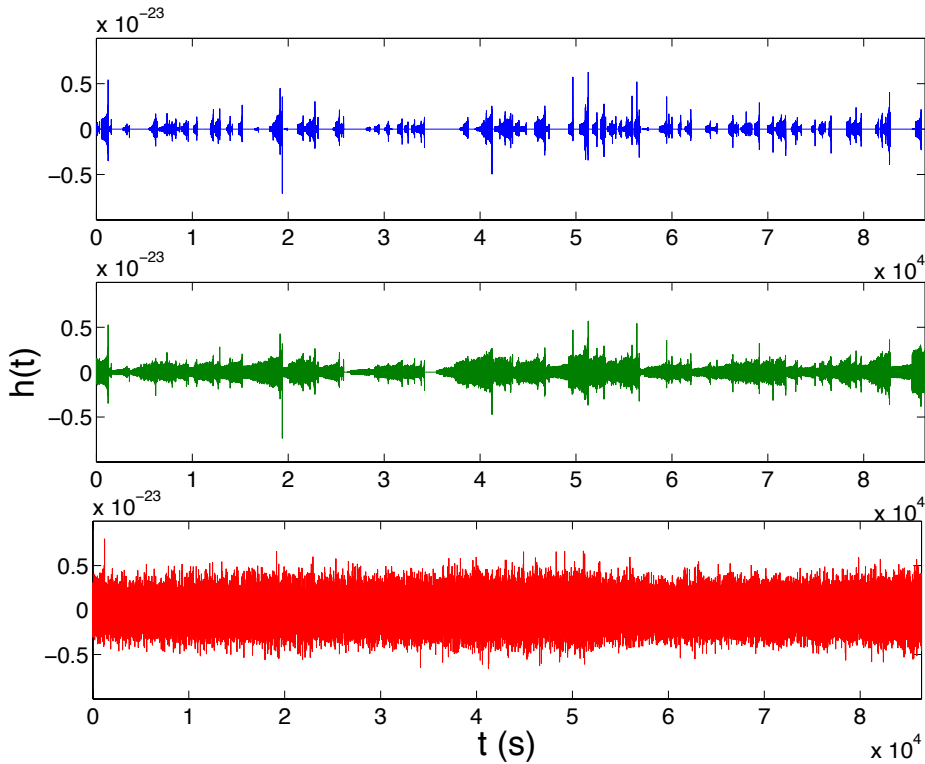


FIG. 9: Time series of length 8192 s, containing the population of BNS (simple model) up to a maximal redshift of $z_{\max} = 0.5$, with minimal frequency 10 Hz (top), 5 Hz (middle) and 1Hz (bottom).

multiply the GW signal $h(t)$ by a factor of 3. The duration is not a power of 2 so the option ‘-L 2048’ tells the code to generate 2048 s noise segments.

It is possible to generate data for Virgo using the flag ‘--virgo’. This will generate an extra frame in the directory **output** (V1:STRAIN-800004096-2048.gwf).

Remark: It is important to use the same duration, minimal frequency and starting time used to produce the list files.

VIII. STOCHASTIC STUDIES

A few options have been added to the data generation code to facilitate stochastic studies and the development of new data analysis methods.

1. ./simul -t 800000000 -j 2 -l 2048 -r 4096 -f 10 --noise --sgwb -i 3 -o 1e-6 -F 100 -H 0.7

The flag “--sgwb” will produce frames with a stochastic GW background of the form $\Omega_{gw}(f) = \Omega_{ref}(f/f_{ref})^\alpha$, generated in the frequency domain, with a power index $\alpha = 3$ and a reference value of $\Omega_{ref} = 10^{-6}$ at the reference frequency $f_{ref} = 100$ Hz. The Hubble parameter will be assumed to be $h_0 = 0.7$.

2. ./simul -t 800000000 -j 2 -l 2048 -r 4096 -f 10 --noise --agwb -w 0 -b 100 -B 0.1 -m 0.1

This will generate frames with a GW background of sine-gaussian waveforms with frequency $f_0 = 100$ Hz, damping time $\tau = 0.1$ s and duty cycle $\mu = 0.1$. As for CBC, the event times are selected from a Poisson distribution. The average time interval is defined by the duty cycle and the damping time as $\Delta t = \tau/\mu$.

We have also a few useful codes to study the background formed by all the CBCs (most of them are not included in the package but can be sent separately). The code *background.c* estimates analytically the spectrum $\Omega_{gw}(f)$ of the background created by all the CBC sources in the data set. It reads the parameters of the sources in the file *list_cbc.txt* created by *list_cbc.c*.

The menu can be displayed with the option -h:

Usage: pipeline [options]

Options:

--print display omega for the reference frequency
--average uses expression of omega averaged over orientation
--ET calculate GW PSD for the 3 ET detectors
--ALV calculate PSD for the 3 ALV detectors
--noIM subtract IMBBH and IMRI
-f minimal frequency
-F reference frequency
-t CBC type (0: all 1:BNS 2:BHNS 3:BBH 4:IMRI 5:IMBBH_GC 6:IMBBH_seed,
-T duration

```

-a amplitude factor
-H Hubble parameter
-h print this message

```

The commands :

```

./list_cbc -S 1000 -l 2048 -r 4096 - f 10 -t 800000000 -d 20 -p 0.85 -P 0.02 -q 0.13 -Q 0
-j 0 -J 0 -z 0 -Z 5 --proba -m 1 -M 3 -a 1.4 -b 0.1 -n 5 -N 13 -u 9 -v 1

```

```

./back -T 2048000 -f 10 -t 1 -a 3 --print F 100

```

first produce the list of CBC parameters *list_cbc.txt* in **input** which is then read by **background.c** to calculate the spectrum $\Omega_{gw}(f)$. It is important to use the same observation time used to produce the list (here 1000×2048) and the same amplitude factor we want to inject.

With the options ‘---print’ -F 100, the value of $\Omega_{gw}(f)$ at the reference frequency 100 Hz is displayed. If the flag ‘--average’ is selected, the code uses an expression of Ω_{gw} averaged over source orientation, otherwise, it uses the values of the inclination in *list_cbc.txt*. The output file *omega.txt* contains the frequency, $\Omega_{gw}(f)$ and also the spectral energy density $S_h(f)$. The flags ‘--ET’ or ‘--ALV’ calculates also the observed PSD taking into account the geometry and the location of the detectors. The extra file *psd_gw.txt* contains the frequency, the ”isotropic” PSD (simply $(\sin^2\alpha/5)Sh(f)$ where α is the arm separation) and the PSDs calculated from the positions in *list_cbc.txt* for all the detectors. Fig. 10 show the spectrum injected in the first 2048000 s of the second ET-MDC.

IX. DEVELOPMENT

This package is still being developed. At that time it is complete enough to produce simple data for mock data challenges in view of the preparation for the Advanced detector era and ET. In the future, the package will be made more user friendly, and will include a few more options like glitchy noise, the use of galaxy catalogs to model

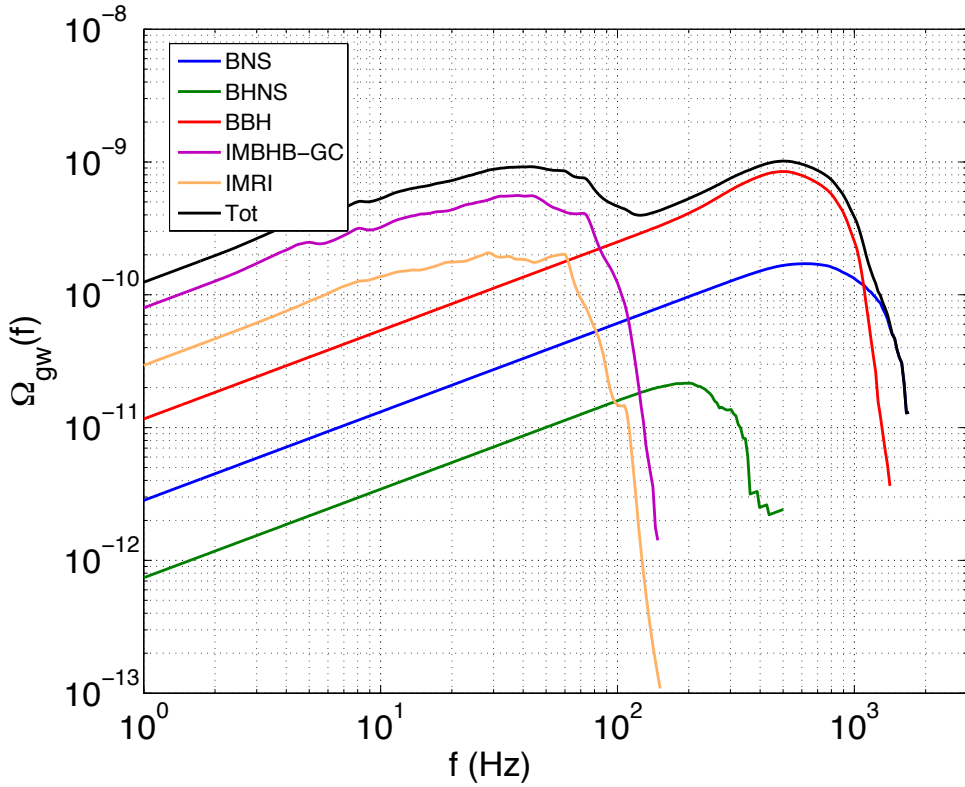


FIG. 10: Energy density of the population of CBC injected in the second ET MDC

the close Universe, pulsars, cosmic strings.

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